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Utilizing Mechanical Linear Transducers for the Determination of a Mining Machine's Position and Heading: The Concept

By Christopher C. Jobes

U.S. DEPARTMENT OF THE INTERIOR
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ILLUSTRATIONS

UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

dB	decibel	μV	microvolt
°C	degree Celsius	μV/°C	microvolt per degree Celsius
ft	foot	mV	millivolt
ft/s	foot per second	oz	ounce
Hz	hertz	pct	percent
in	inch	ppm	part per million
kHz	kilohertz	V	volt
kohm	kilohm	V dc	volt, direct current
lb	pound	V/in	volt per inch
μs	microsecond	°/s	degree per second

UTILIZING MECHANICAL LINEAR TRANSDUCERS FOR THE DETERMINATION OF A MINING MACHINE'S POSITION AND HEADING: THE CONCEPT

By Christopher C. Jobes[1]

ABSTRACT

This U.S. Bureau of Mines report describes a system to determine the position and heading of a mining machine during maneuvers in the face area of an operating mine section. The system is the first step in the development of a guidance system for automated mining machines. The position and heading algorithm is described, and a preliminary error analysis is performed.

The sensors employed were linear position transducers mounted on a mining machine with their cables attached to points on a stationary reference. Four linear position transducers were used to provide a data redundancy that increased the reliability of the guidance system.

The linear position information obtained from the transducers was processed mathematically via the position and heading algorithm to provide the desired position and heading information. The algorithm takes advantage of sensor redundancy to continually test the accuracy of the sensor data.

The major sources of error were determined to be the linear position transducers, the analog-to-digital (A/D) converter used to interpret the data, and the sampling frequency of the measurement system. These sources of error were evaluated to determine their inaccuracies for use in calculating the overall system accuracy.

[1]Mechanical engineer, Pittsburgh Research Center, U.S. Bureau of Mines, Pittsburgh, PA.

INTRODUCTION

Navigation is one of the key systems that must be developed if a mining machine can be automated and the machine operator can be moved to a safe, protected area. This report describes the approach taken by the U.S. Bureau of Mines to solve navigation requirements for maneuvering a continuous miner at the coal mine face. This work is part of the Bureau's program to enhance mine safety.

The function of a position and heading system for a mining machine is to provide guidance information for navigation in the face area. This system must be attained before face operations can be automated under current continuous mining practices.[2] The automation of equipment at the face will increase health, safety, and efficiency in this area. To get a better feel for navigational requirements in mining, it is necessary to briefly look at navigation in mines as it is currently performed by workers.

Navigation in a mine can be divided into three categories: global navigation, local navigation, and face navigation.[3] Each of these navigation categories requires the performance of various navigational tasks.

GLOBAL NAVIGATION

Global navigation consists of the navigation of a piece of mobile mining equipment from one place in a mine to another that cannot be seen. This is similar to driving an automobile from one city to another. The travel of a mantrip is a good example of this form of navigation as it may cover several miles. Operators of supply and maintenance vehicles also perform this type of navigation on a regular basis. The operators of all mobile mining equipment, at one time or another, must perform this type of navigation to get from the surface to their assigned workplace. Their tasks usually include, among other things, mine mapping, path generation, and path following.

The primary task in global navigation is to move a mining machine from one place in the mine to another. The major resource for accomplishing a navigational task is the mine map. A mine map is continually updated as changes are made to, or occur in, the mine. These changes are usually noted on the mine map as they occur since they may affect navigational decisions. Such changes may include roof falls, stoppings, dangerous conditions, unnavigable portions, etc.

Using a mine map, knowledge of the initial position and desired destination, and path generation rules, a guidance system can usually generate a path from one place in a mine to another. The generation of this path may take into consideration several items: the normally used path, mine conditions along that path, traffic, etc. This form of path generation usually determines which entries must be traveled and where turns must be made.

When a guidance system follows a generated path, the current position must be continually updated on the mine map as well as the generated path. As the mining machine follows the generated path, it must negotiate entries and corners and must also perform collision avoidance, implemented by manipulating the configuration, position, and orientation of the machine.

LOCAL NAVIGATION

Local navigation is performed within the area of the mine that the guidance system sensors can see. Local navigation includes traversing entries and turning crosscuts in the performance of some navigational task (e.g., path following). The local navigational tasks include scheduling as well as the normal mine mapping, path generation, and path following functions.

The local map must be of greater detail than the mine map. It should be updated more frequently and should include the location of all pieces of mining equipment and their function. This information will be of use to the scheduling algorithm.

The movement of one piece of mining equipment from one place in the local area to another requires some form of scheduling since there is a good amount of activity and equipment present in the average continuous mining section. Scheduling is required since there is a cycle of tasks to be performed at the face requiring the application of several pieces of equipment (continuous miners, shuttle cars, roof bolters, rock dusters, etc.) among the faces being mined. The performance of these tasks needs to be coordinated so that there is a minimal amount of interference among the tasks performed, thus maximizing the efficiency and therefore the productivity of the section.

The path generation and path following tasks are much the same as in global navigation, with only a few added complications. If shuttle cars are present in the mining section, it may be necessary to avoid their trailing cables if they are located in the entry being traveled. Also, there is a greater need of care in collision avoidance since there are more items hanging from the roof, attached to the ribs, or parked in the entries.

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[2]Schnakenberg, G. H., Jr. Computer-Assisted Continuous Coal Mining System–Research Program Overview. BuMines IC 9227, 1989, 15 pp.

[3]Anderson, D. L. Framework for Autonomous Navigation of a Continuous Mining Machine: Face Navigation. BuMines IC 9214, 1989, 23 pp.

FACE NAVIGATION

Face navigation is performed by mobile mining equipment preparing to perform a task in the face area of an entry or crosscut development. The type of equipment in the face area may include mining equipment such as continuous mining machines and roof bolters. The face navigational tasks include mine mapping, path generation, and path following.

The map of the face area should be of the greatest detail and should be updated frequently. The updated information should include the volume created by coal extraction, the location and types of roof bolts applied in the face area, the local geology (which may be determined by monitoring the virtual work during the drilling cycle), etc.

The path generation and path following tasks are similar to those of local and global navigation, but include some additional tasks. Path generation for coal extraction must be in accordance with predetermined mining patterns and must develop the entry according to the mine plan. Path following must be fairly exact and must function in accordance with the type of machine being guided (i.e., the cutting drum diameter would determine the distance of sump for a continuous mining machine).

The actual guidance of the mining machine is of great importance to the mining cycle since much depends on face navigation. This guidance task is important since the conditions and obstacles are a hindrance to the implementation of a guidance system.

BACKGROUND

Many designs of navigational systems for use with autonomous self-guided mining machines have been attempted in prior years. These attempts can be categorized into electromagnetic, stress wave, and mechanical methods. While there is much work being done in the electromagnetic (optical, laser, radar, magnetic compass, natural gamma, etc.) and stress wave (ultrasonic, seismic, vibration, etc.) areas, very little attention is being paid to mechanical guidance systems.

The apparent reason for the lack of interest in mechanical guidance systems is that this method usually involves either dead reckoning (e.g., sensing wheel motion) or mechanical attachment. In dead reckoning, the errors introduced into the system are cumulative, and therefore a system relying on this form of navigation alone is unreliable, particularly in a mining environment. Most mining machine designers seem unwilling to restrict the motion of their machines enough for a mechanical attachment system to be a viable option.

One known attempt has been made at using an attachment method for the guidance of a mining machine. In particular, a trolley-pole-type articulated boom (fig. 1) is used to guide a roadheader.[4] This articulated boom has six degrees of freedom (fig. 2) that are instrumented (one prismatic and five revolute). This method uses standard robot kinematics techniques to determine the position and orientation of the roadheader with respect to the local reference frame. The system performed adequately, but was not considered for use since there was not enough overhead room available to the continuous mining machine.

PROBLEM DEFINITION

A system for machine guidance was required to determine the position and heading of a mining machine during maneuvers required in the face area of an entry. To adequately design the mechanical system, it was necessary to first define the system's requirements and constraints.

TOPOLOGICAL REQUIREMENTS

Topological requirements are the minimum set of parameters to be defined before the kinematic chain of a mechanism can systematically be enumerated. Usually this includes the "space" (planar or spatial) in which the mechanism moves, the degree of freedom, and either the number of links or independent loops needed to obtain a finite solution set. At this point in the design procedure, any additional specifications should be made to reduce the number of solutions even further.

The nature of motion of a mining machine in a coal seam was determined to be spatial rather than planar since it cannot be assumed that the coal seam would be absolutely smooth for even a short distance. Thus, the mining machine was determined to have six degrees of freedom (x, y, z, roll, pitch, and yaw).

[4]British Coal, Headquarters Technical Department (Burton on Trent, England). Alignment and Profile Guidance of Roadheaders. Final report on European Coal and Steel Community Research Project 7220-AB/810, 1987, 45 pp.

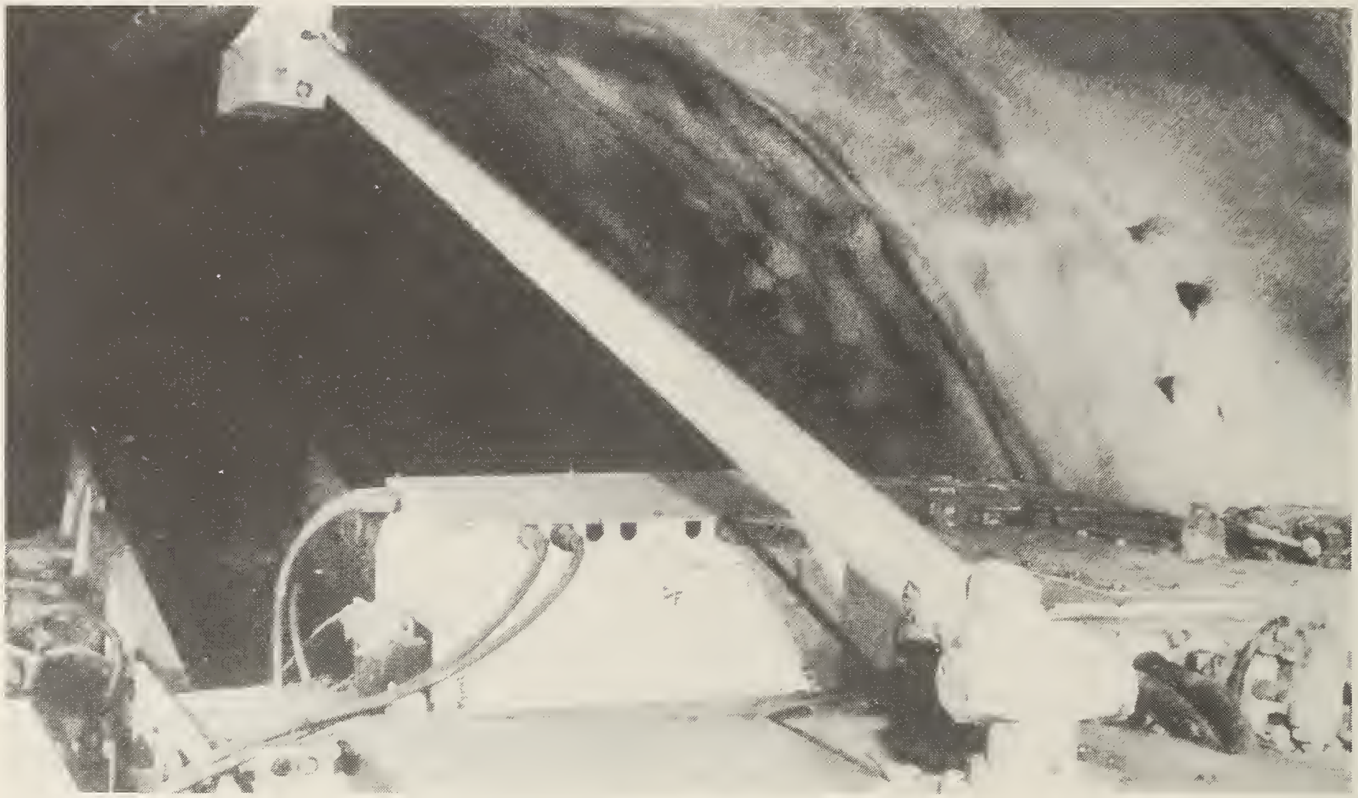


Figure 1.–British Coal trolley-pole-type articulated boom.

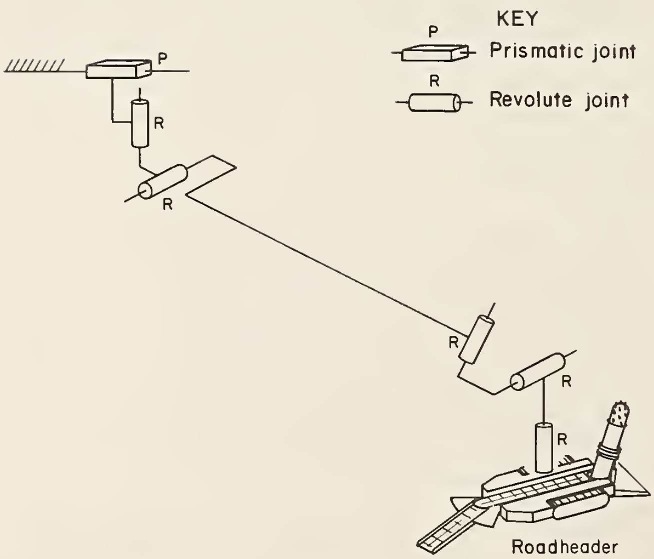


Figure 2.–Instrumented degrees of freedom on trolley-pole-type articulated boom.

The degree of freedom of the system was dependent on the number of independent inputs to the system. In this case, the mining machine was the input to the guidance system and therefore the system had six degrees of freedom. This degree of freedom required that any kinematic chain connecting the mining machine to the local reference frame have at least six degrees of freedom to work properly.

FUNCTIONAL REQUIREMENTS

Functional requirements are the tasks to be performed by the mechanism. The only task of this mechanism is the tracking of the position and orientation of the mining machine. In order for the tracking to be accomplished without unnecessary redundancy, no more than six degrees of freedom were required to connect the mining machine to the local reference frame.

CONSTRAINTS

When the mechanism was designed, there were two types of constraints: dimensional and inertial. These constraints determined the feasibility of any mechanisms that were found to satisfy the topological and functional requirements.

Dimensional Constraints

Some of the dimensional constraints on the mechanism connecting the mining machine to the local reference frame were that the mechanism–

1. Should perform the required task within the entry in which the mining machine is to be working while minimizing contact with the ribs or uncut coal blocks since such contact may or may not result in damage to the mechanism.
2. Should minimize its interference with the mining machine's task since its purpose is to measure, not to be an avoided object.
3. Should allow up to a 40-ft advance or a 20-ft, 90° crosscut to maximize productivity during the automated cutting cycle.
4. Must avoid interference with the mining machine conveyor boom and shuttle car (if continuous haulage is not being used) since such contact would interfere with reliable measurement and may result in damage to the mechanism.
5. Must avoid the ventilation curtain (if present) since contact with the curtain may affect one or more of the transducers.

Inertial Constraints

Some of the inertial constraints on the mechanism connecting the mining machine to the local reference frame were, as follows:

1. The inertia of the mechanism should be minimized to reduce the loading of the mining machine and the mechanism's resolving joints.
2. The mass of the mechanism must be minimized to reduce its interference with the operation of the mining machine.
3. The mechanism must be stiff enough to maintain accurate measurements during the movements of the mining machine.

POSITION AND HEADING SYSTEM

To develop the position and heading system, the transducers to be used were selected first. Next, the configuration of the sensors was addressed so that the accuracy and reliability of the position and heading system were maximized. Finally, the number of sensors was made redundant so that the reliability of the position and heading system could be continuously monitored.

SENSOR SELECTION

In the average coal seam, the headroom available to the position and heading system is less than that available to the British Coal roadheader guidance system. Therefore, an articulated boom was not considered to be the best type of connection to make. Aside from the fact that it was a cumbersome way to go about measuring the position and heading of a mining machine, it would have been big and heavy. Because of the weight and length of the system, it was possible to foresee a problem with oscillations in the boom that would reduce the life of the measurement system and reduce the accuracy of the measurement readings. It would be very difficult to make a 40- to 50-ft-long boom stiff enough for accurate measurement without also making it too big for the job (i.e., cumbersome with a corresponding lack of mobility).

Since not all of the degrees of freedom of the links connecting the mining machine to the local reference frame needed to be instrumented, several groups of links (called chains) or their equivalents were used. Furthermore, while the motion of the mining machine was in six degrees of freedom, not all of the motions were considered large enough to require measurement. (Although coal seams are not "flat," the generally accepted change in gradient does not typically exceed 5° over an occasional roll between 20 to 50 ft wide within the northern Appalachian coal seams.) Therefore, for a relatively smooth seam, the z, roll, and pitch measurements could be assumed to have a negligible effect on the x, y, and yaw measurements (position and heading) with respect to other sources of error. If such information was needed, it would be possible to use roll and pitch sensors on the mining machine to adjust for such errors relative to a leveled local reference. Thus, the sensor selection task was one of determining which six-degree-of-freedom chain could best perform the position and heading measurements, but not all of whose degrees of freedom need to be instrumented.

Given that most transducers measure only one degree of freedom and few had the necessary linear range, the list of possible mechanical attachment measurement schemes was reduced to a linear position transducer, or wire pull (fig. 3), as it is sometimes called. Although each linear position transducer technically has an infinite number of degrees of freedom, each wire was modeled as a six-degree-of-freedom kinematic chain equivalent (fig. 4). Thus, the position and heading system development task became a method of configuring linear position transducers to perform the position and heading measurement task.

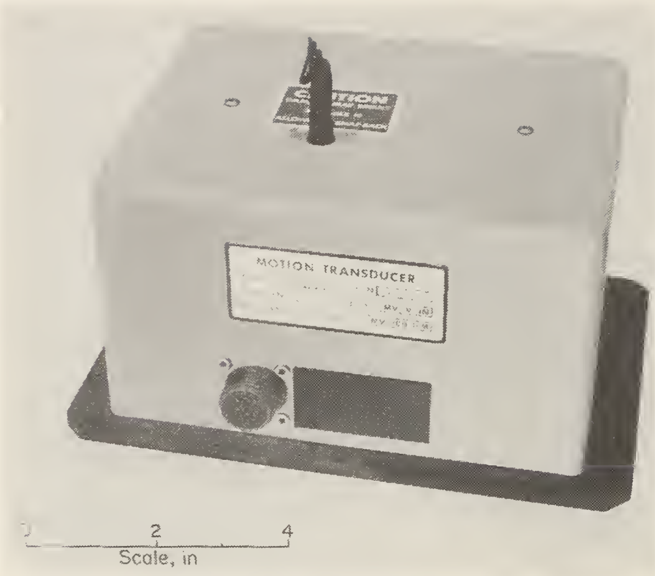


Figure 3.–Linear position transducer.

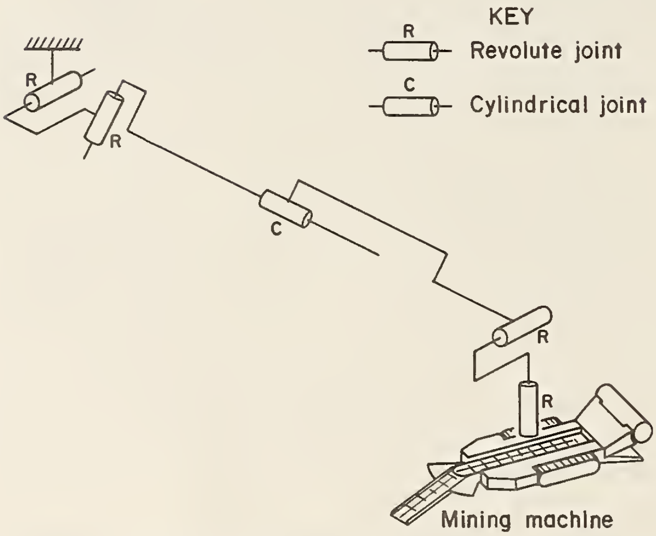


Figure 4.–Kinematic equivalent of linear position transducer.

SENSOR CONFIGURATION

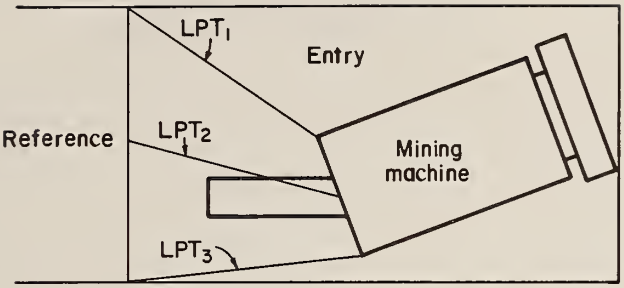
The task of finding a configuration in which the linear position transducers could be used to determine the position and heading of a mining machine was relatively simple. While it was possible to perform the required measurement with one linear transducer and two revolute transducers to measure the departure angle of the wire relative to the local and machine reference frames, there was no such transducer on the market. This configuration was deemed to be low in accuracy because the linear transducers had a relatively light "pull" (about 3 lb), and this configuration would not be redundant and therefore could be tested for accuracy. Therefore, three linear position transducers were deemed required to determine the three measured degrees of freedom (position and heading). The placement of these transducers and the attachment of their cables made little difference in the ability to calculate the position and heading of the mining machine, provided the cables were not parallel and the attachment points and transducer locations were separated by a sufficient distance to reduce the linear position transducer error to a reasonable percentage. The placement of the transducers did, however, affect the computation required for the calculation. If the linear position transducers were located as shown in the top portion of figure 5, a set of nonlinear transcendental equations occurred and an iterative solution method was required. If the linear position transducers were located as shown in the bottom portion of figure 5, the solution to the position and heading equations could be arrived at easily using elementary trigonometry. However, because of the nature of the trigonometric equations, some ambiguities arose that resulted in multiple possible machine positions and headings for a given set of sensor readings.

REDUNDANT SENSOR CONFIGURATION

An easy method to solve a portion of the multiple solution problem arising from ambiguities in the trigonometric derivation was to add a redundant sensor (fig. 6). This sensor served two purposes. The first purpose was to identify which of the multiple solutions was the correct one by first performing a very simple four-transducer solution. The other purpose was to compare the four three-transducer solutions with the four-transducer solution to see if one of the four linear position transducers was furnishing erroneous data.

A transducer error would show up as all of the four three-transducer solutions being different from each other, since only one solution did not use the suspect transducer. Of course in this case, the four-transducer solution was also incorrect. If more than one transducer was giving erroneous data, every three-transducer solution could yield a different position and heading. This was, however, preferable to the case with a single three-transducer solution where it was never really known if the solution was correct.

Using this information, the mining machine could be guided using the four-transducer solution. A correct solution could still be found, however, if the initial configuration and the sign of angular rotation of the mining machine was known. If a valid solution was not obtainable, then the mining machine controller could shut down the mining machine and request maintenance.



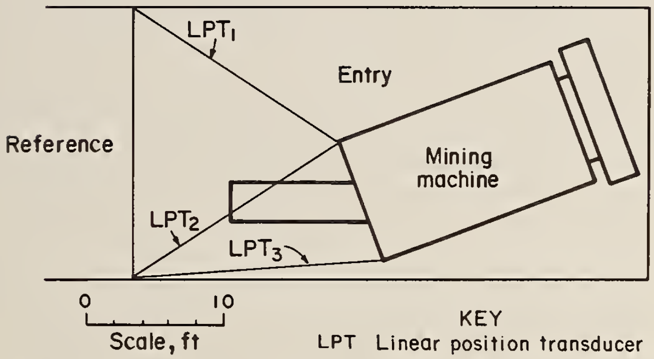


Figure 5.–Three-transducer configuration. Top, requiring iterative solution; bottom, directly solvable.

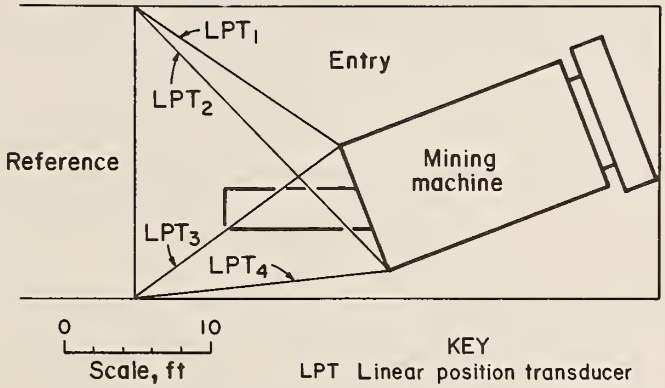


Figure 6.–Directly solvable redundant four-transducer configuration.

POSITION AND HEADING ALGORITHM

In developing the position and heading algorithm, the first task was to define the reference frames used. The next task was to develop the coordinate transformation of the reference frames. Finally, a closed-form solution of the position and heading algorithm was developed.

DEFINITION OF REFERENCE FRAMES

In mechanism analysis, the location of an object was of some concern. In order to describe an object's position in space, a coordinate system or frame was attached to the object. The position and orientation of the frame was then described with respect to some reference coordinate frame. For the purpose of this research, a local reference frame was attached to ground at some distance behind the mining machine. The machine reference frame was attached to some point on the mining machine (fig. 7). A reference frame was denoted by the prefix superscripts, A, for the local reference frame, and B, for the mining machine's reference frame.

It was essential that some notation be defined before coordinate transformations could be addressed. The position vector was represented by a bold-faced character (**R**). This character represented the position in space of a point relative to the associated reference frame. For a two-dimensional example, the position vector either described an (x,y) point in rectangular coordinate form or an (r,θ) point in polar coordinate form (fig. 8). The notation for the components of a vector in the rectangular coordinate system was

$$x_i \text{ or } y_i,$$

where i = vector number,

x = x component of position vector,

and y = y component of position vector.

The notation for the components of a vector in the polar coordinate system was

$$r_i \text{ or } \theta_i,$$

where i = vector number,

r = magnitude of position vector,

and θ = direction of the position vector relative to positive x axis.

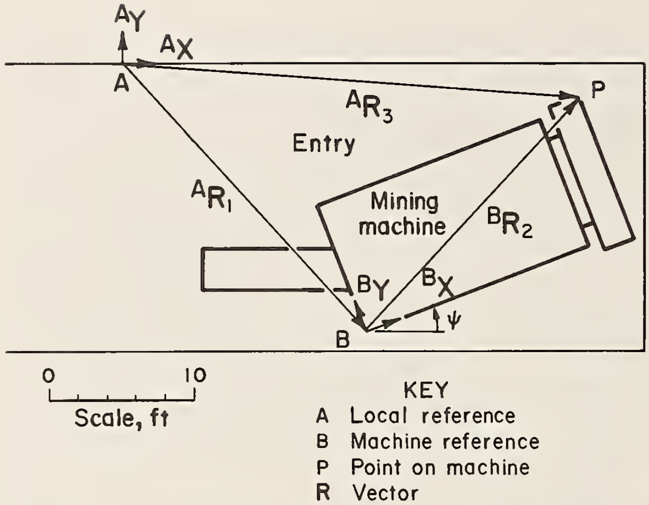


Figure 7.–Local and machine reference frames and position vectors.

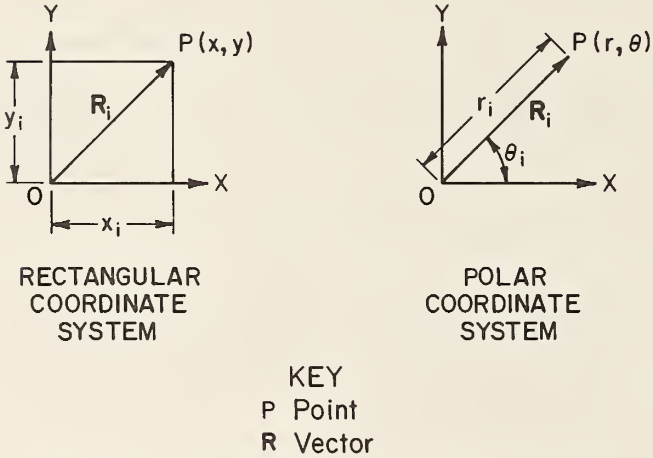


Figure 8.–Rectangular and polar coordinate components.

The relationship between the rectangular and polar coordinate systems was

$$x = r\cos(\theta) \text{ and } y = r\sin(\theta),$$

with the corresponding inverses

$$r = (x^2 + y^2)^{1/2} \text{ and } \theta = \tan^{-1}(y/x).$$

Finally, in matrix notation, the rectangular form was shown as

$$\begin{bmatrix} x \\ y \end{bmatrix} \text{ or } \begin{bmatrix} r\cos(\theta) \\ r\sin(\theta) \end{bmatrix}.$$

COORDINATE TRANSFORMATION OF REFERENCE FRAMES

Since the mining machine reference frame moved with respect to the local reference frame with three degrees of freedom, coordinate transformations were required to transform position vectors expressed in the mining machine coordinate system into position vectors relative to the local reference frame. This transformation is standard procedure in robot kinematics. The process was almost trivial since there were only two reference frames in this case.

Consider again figure 7. If only the position vectors $^{A}\mathbf{R}_1$ and $^{B}\mathbf{R}_2$ were known, elementary vector algebra would have dictated that the sum of the two would equal $^{A}\mathbf{R}_3$. That was not true in this case, however, since $^{B}\mathbf{R}_2$ was not measured in the local coordinate frame. If a transform $^{A}_{B}\mathbf{T}$ was available to convert the position vector from the machine coordinate frame into the local coordinate frame by a rotation operation of ψ degrees, then the resulting equation would be

$$^{A}\mathbf{R}_3 = {}^{A}\mathbf{R}_1 + {}^{A}_{B}\mathbf{T}\,{}^{B}\mathbf{R}_2. \tag{1}$$

If $\quad ^{A}\mathbf{R}_1$ = (17,-18) in local reference frame,

$\quad ^{B}\mathbf{R}_2$ = (20,10) in machine reference frame,

and $\quad \psi$ = heading of 20° in local reference frame,

then it could be shown that

$\quad ^{A}\mathbf{R}_3$ = (32,-2) in local reference frame.

Letting the rotation transform

$$^{A}_{B}\mathbf{T} = \begin{bmatrix} \cos(\psi) & -\sin(\psi) \\ \sin(\psi) & \cos(\psi) \end{bmatrix} \tag{2}$$

and substituting the known values into equation 1 yielded

$$\begin{bmatrix} 17 \\ -18 \end{bmatrix} + \begin{bmatrix} \cos(20°) & -\sin(20°) \\ \sin(20°) & \cos(20°) \end{bmatrix} \begin{bmatrix} 20 \\ 10 \end{bmatrix} = \begin{bmatrix} 17 \\ -18 \end{bmatrix} + \begin{bmatrix} 15 \\ 16 \end{bmatrix}$$

$$= \begin{bmatrix} 32 \\ -2 \end{bmatrix}.$$

It should be noted here that

$$\begin{bmatrix} 15 \\ 16 \end{bmatrix} = {}^{A}\mathbf{R}_2.$$

This is the standard method for performing kinematic analysis of mechanisms in a plane, which was used during the development of the closed-form solution of the position and heading algorithm.

CLOSED-FORM SOLUTION

The standard solution method for kinematic problems involving more than one reference frame (coordinate transformation analysis of a planar mechanism) was applied to this position and heading system. While the chosen configuration of the position and heading system made the problem simple enough to handle by elementary trigonometric solution methods, the coordinate transformation analysis method was determined to be general enough to be applied to all possible configurations of the linear transducers, whereas of the infinite number of configurations, only a finite number could be addressed utilizing standard trigonometric techniques.

Before a closed-form solution for the position and heading algorithm could be performed, the linear position transducers were configured for use and all the position vectors of interest were defined (fig. 9). The first step in developing the position and heading algorithm was to write the loop equations for a three-transducer solution and to determine if the equations could be reduced into a directly solvable form. The next step was to determine the closed-form solution. A four-transducer solution was then found from the closed-form solutions for the four three-transducer solutions. Finally, a strategy was developed in which the three-transducer solutions were used to test the validity of the four-transducer solution and to provide a backup solution should one transducer provide erroneous data.

Loop Equation Development

Four loop equations were written from the configuration shown in figure 9, as follows:

$$ {}^{A}R_1 + {}^{A}R_4 - {}^{A}_{B}T\,{}^{B}R_9 - {}^{A}R_{11} = 0, \tag{3}$$

$$ {}^{A}R_1 + {}^{A}R_5 - {}^{A}_{B}T\,{}^{B}R_{10} - {}^{A}R_{11} = 0, \tag{4}$$

$$ {}^{A}R_2 + {}^{A}R_6 - {}^{A}_{B}T\,{}^{B}R_9 - {}^{A}R_{11} = 0, \tag{5}$$

and

$$ {}^{A}R_2 + {}^{A}R_7 - {}^{A}_{B}T\,{}^{B}R_{10} - {}^{A}R_{11} = 0. \tag{6}$$

These four vector loop equations represented eight scalar equations and seven unknowns. Thus, the four-transducer solution was overconstrained, which was to be expected since the fourth transducer was added to provide redundancy. Thus, the three-transducer solutions are derived first using the four combinations of three equations representing six scalar equations and six unknowns.

Three-Transducer Solution

The three-transducer solution derived here used vector loop equations 3, 4, and 5 (i.e., ignored data from transducer 4). To reduce the order of the equations, ${}^{A}R_{11}$ was eliminated by subtracting equations 5 and 4 from equation 3, yielding

$$ {}^{A}R_1 - {}^{A}R_2 + {}^{A}R_4 - {}^{A}R_6 = 0 \tag{7}$$

and

$$ {}^{A}R_4 - {}^{A}R_5 - {}^{A}_{B}T\,{}^{B}R_9 + {}^{A}_{B}T\,{}^{B}R_{10} = 0. \tag{8}$$

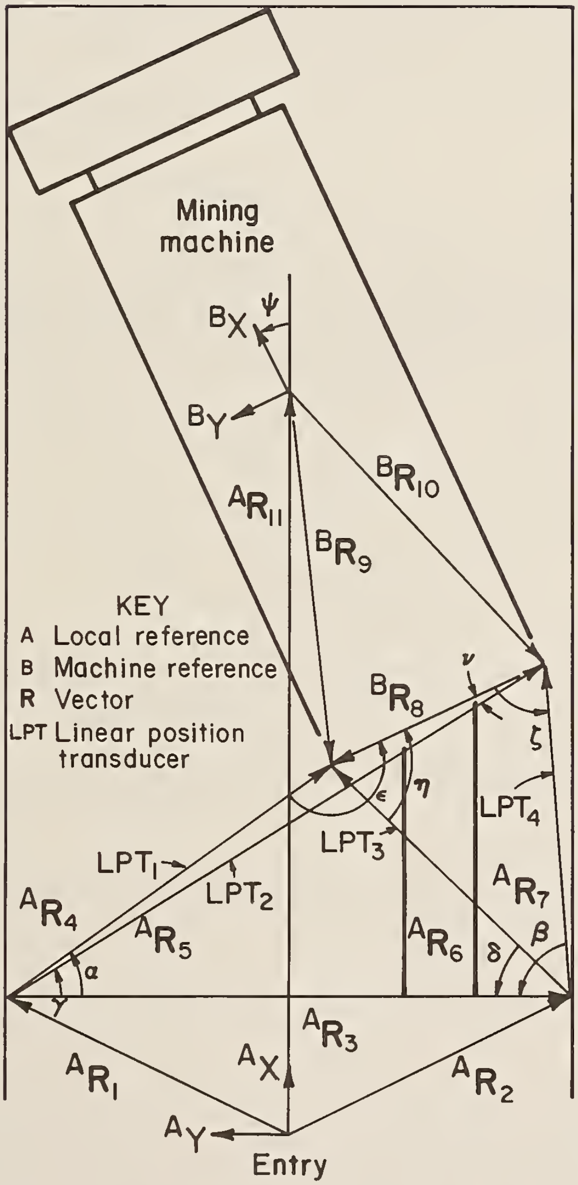


Figure 9.–Configuration for position and heading algorithm.

Then, by substituting

$$^{A}\mathbf{R}_2 - {}^{A}\mathbf{R}_1 = {}^{A}\mathbf{R}_3 \quad (9)$$

and

$$^{B}\mathbf{R}_9 - {}^{B}\mathbf{R}_{10} = {}^{B}\mathbf{R}_8, \quad (10)$$

equations 7 and 8 became

$$^{A}\mathbf{R}_4 - {}^{A}\mathbf{R}_3 - {}^{A}\mathbf{R}_6 = \mathbf{0} \quad (11)$$

and

$$^{A}\mathbf{R}_4 - {}^{A}\mathbf{R}_5 - {}^{A}_{B}\mathbf{T}\,{}^{B}\mathbf{R}_8 = \mathbf{0}. \quad (12)$$

Vector equation 11 had two scalar equations and only two unknowns (θ_4 and θ_6) and could, therefore, be solved directly in the following manner:

Letting

$$\alpha = \theta_4 - \theta_3 \quad (13)$$

and

$$\delta = \theta_3 + \pi - \theta_6. \quad (14)$$

The scalar equations were separated and the trigonometric identities $\cos(\alpha+\pi) = -\cos(\alpha)$ and $\sin(\alpha+\pi) = -\sin(\alpha)$ are used. (Hereafter, $c\theta$ and $s\theta$, the kinematic shorthand for $\cos(\theta)$ and $\sin(\theta)$, will be used.)

$$\begin{bmatrix} r_4c(\alpha + \theta_3) \\ r_4s(\alpha + \theta_3) \end{bmatrix} - \begin{bmatrix} r_3c\theta_3 \\ r_3s\theta_3 \end{bmatrix} + \begin{bmatrix} r_6c(\theta_3 - \delta) \\ r_6s(\theta_3 - \delta) \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}. \quad (15)$$

The x scalar equation component was solved for δ:

$$\delta = \pm\cos^{-1}\left[\frac{r_3c\theta_3 - r_4c(\alpha + \theta_3)}{r_6}\right] + \theta_3, \quad (16)$$

and δ was substituted into y scalar equation component of equation 15 using the identity $\sin[\cos^{-1}(x)] = (1 - x^2)^{1/2}$,

$$[r_6^2 - (r_3c\theta_3 - r_4c(\alpha + \theta_3))^2]^{1/2} + r_4s(\alpha + \theta_3)$$
$$- r_3s\theta_3 = 0. \quad (17)$$

The square root was isolated on the left side of the equation and both sides were squared, yielding

$$r_6^2 - r_3^2c^2\theta_3 + 2r_3r_4c\theta_3c(\alpha + \theta_3) - r_4^2c^2(\alpha + \theta_3)$$
$$= r_3^2s^2\theta_3 - 2r_3r_4s\theta_3s(\alpha + \theta_3) + r_4^2s^2(\alpha + \theta_3). \quad (18)$$

Using the identities $\sin^2(\theta) + \cos^2(\theta) = 1$ and $\cos(\alpha)\cos(\beta) + \sin(\alpha)\sin(\beta) = \cos(\alpha-\beta)$, equation 18 reduced to

$$r_6^2 = r_3^2 + r_4^2 - 2r_3r_4c\alpha, \quad (19)$$

which was essentially an application of the law of cosines to a triangle whose sides are known. Thus, since

$$\alpha = \pm\cos^{-1}\left[\frac{r_3^2 + r_4^2 - r_6^2}{2r_3r_4}\right], \quad (20)$$

equation 13 was solved to find

$$\theta_4 = \theta_3 + \alpha. \quad (21)$$

Since α is determined by the inverse cosine function, there are actually two solutions to equation 21, since $\cos(-\alpha) = \cos(\alpha)$. One must therefore assume that the mining machine transducer attachment points will always be to the positive x side of the line connecting the transducer cable attachment points and therefore take the positive value of α. Thus, when θ_4, θ_5, θ_6, and θ_7 are calculated, the upper signs in the equations are to be used.

Now, since θ_4 is known, equation 12 only had two unknowns (θ_5 and ψ) and could be solved in the same manner as equation 11, letting

$$\epsilon = \theta_8 + \psi - \theta_4 \quad (22)$$

and

$$\nu = \theta_5 - \psi + \pi - \theta_8. \quad (23)$$

Separating the scalar equations

$$\begin{bmatrix} r_4c(\theta_8 + \psi - \epsilon) \\ r_4s(\theta_8 + \psi - \epsilon) \end{bmatrix} + \begin{bmatrix} r_5c(\nu + \theta_8) \\ r_5s(\nu + \theta_8) \end{bmatrix}$$
$$- \begin{bmatrix} c\psi & -s\psi \\ s\psi & c\psi \end{bmatrix} \begin{bmatrix} r_8c\theta_8 \\ r_8s\theta_8 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}. \quad (24)$$

The x scalar equation component was solved for ν

$$\nu = \pm\cos^{-1}\left[\frac{r_8c(\theta_8 + \psi) - r_4c(\theta_8 + \psi - \epsilon)}{r_5}\right] - \theta_8, \quad (25)$$

and ν was substituted into the y scalar equation component of equation 24:

$$r_4s(\theta_8 + \psi - \epsilon) + (r_5^2 - (r_8c(\theta_8 + \psi)$$
$$- r_4c(\theta_8 + \psi - \epsilon))^2)^{1/2} - r_8s(\theta_8 + \psi) = 0. \quad (26)$$

The square root was isolated on the left side of the equation and both sides were squared yielding

$$r_5^2 - r_8^2c^2(\theta_8 + \psi) + 2r_8r_4c(\theta_8 + \psi)c(\theta_8 + \psi - \epsilon)$$
$$- r_4^2c^2(\theta_8 + \psi - \epsilon) = r_4^2s^2(\theta_8 + \psi - \epsilon)$$
$$- 2r_4r_8s(\theta_8 + \psi)s(\theta_8 + \psi - \epsilon) + r_8^2s^2(\theta_8 + \psi). \quad (27)$$

Equation 27 reduced to

$$r_5^2 = r_4^2 + r_8^2 - 2r_4r_8c\epsilon, \tag{28}$$

which was essentially an application of the law of cosines to a triangle whose sides are known. Thus, since

$$\epsilon = \pm\cos^{-1}\left[\frac{r_4^2 + r_8^2 - r_5^2}{2r_4r_8}\right], \tag{29}$$

equation 22 was solved to find the mining machine heading.

$$\psi_4 = \pm\epsilon - \theta_8 + \theta_4. \tag{30}$$

(The sign to be used for ϵ cannot be determined unless both the initial configuration and the sign of the angular velocity of the mining machine are known.)

The position of the mining machine could then be determined from equation 3 to have components

$$\begin{bmatrix} r_1c\theta_1 \\ r_1s\theta_1 \end{bmatrix} + \begin{bmatrix} r_4c\theta_4 \\ r_4s\theta_4 \end{bmatrix} - \begin{bmatrix} c\psi_4 & -s\psi_4 \\ s\psi_4 & c\psi_4 \end{bmatrix} \begin{bmatrix} r_9c\theta_9 \\ r_9s\theta_9 \end{bmatrix} = \begin{bmatrix} x_{11} \\ y_{11} \end{bmatrix}; \tag{31}$$

therefore,

$$x_{11} = r_1c\theta_1 + r_4c\theta_4 - r_9c(\theta_9 + \psi_4) \tag{32}$$

and

$$y_{11} = r_1s\theta_1 + r_4s\theta_4 - r_9s(\theta_9 + \psi_4). \tag{33}$$

In summary, the three-transducer solution, which did not use transducer 4 data (i.e., using loop equations 3, 4, and 5), for the mining machine's heading was given by using equations 20, 21, 29, and 30. The mining machine's position was given by equations 32 and 33.

In a similar manner, in a three-transducer solution, which excludes transducer 3 (i.e., using loop equations 3, 4, and 6), the mining machine's heading is given by

$$\gamma = \pm\cos^{-1}\left[\frac{r_3^2 + r_5^2 - r_7^2}{2r_3r_5}\right], \tag{34}$$

$$\theta_5 = \theta_3 \pm \gamma, \tag{35}$$

$$\nu = \pm\cos^{-1}\left[\frac{r_5^2 + r_8^2 - r_4^2}{2r_5r_8}\right], \tag{36}$$

and

$$\psi_3 = \pi - \pm\nu - \theta_8 + \theta_5. \tag{37}$$

The mining machine's position was determined by equation 4 to have components

$$x_{11} = r_1c\theta_1 + r_5c\theta_5 - r_{10}c(\theta_{10} + \psi_3) \tag{38}$$

and

$$y_{11} = r_1s\theta_1 + r_5s\theta_5 - r_{10}s(\theta_{10} + \psi_3). \tag{39}$$

Next, in a three-transducer solution, which excludes transducer 2 (i.e., using loop equations 3, 5, and 6), the mining machine's heading was given by

$$\delta = \pm\cos^{-1}\left[\frac{r_3^2 + r_6^2 - r_4^2}{2r_3r_6}\right], \tag{40}$$

$$\theta_6 = \theta_3 - \pi \mp \delta, \tag{41}$$

$$\eta = \pm\cos^{-1}\left[\frac{r_6^2 + r_8^2 - r_7^2}{2r_6r_8}\right], \tag{42}$$

and

$$\psi_2 = \pm\eta - \theta_8 + \theta_6. \tag{43}$$

The mining machine's position was determined by equation 5 to have components

$$x_{11} = r_2c\theta_2 + r_6c\theta_6 - r_9c(\theta_9 + \psi_2) \tag{44}$$

and

$$y_{11} = r_2s\theta_2 + r_6s\theta_6 - r_9s(\theta_9 + \psi_2). \tag{45}$$

Finally, in the last three-transducer solution, which excludes transducer 1 (i.e., using loop equations 4, 5, and 6), the mining machine's heading was given by

$$\beta = \pm\cos^{-1}\left[\frac{r_3^2 + r_7^2 - r_5^2}{2r_3r_7}\right], \tag{46}$$

$$\theta_7 = \theta_3 - \pi \mp \beta, \tag{47}$$

$$\zeta = \pm\cos^{-1}\left[\frac{r_7^2 + r_8^2 - r_6^2}{2r_7r_8}\right], \tag{48}$$

and

$$\psi_1 = \pi - \pm\zeta - \theta_8 + \theta_7. \tag{49}$$

The mining machine's position was determined by equation 4 to have components

$$x_{11} = r_2c\theta_2 + r_7c\theta_7 - r_{10}c(\theta_{10} + \psi_1) \tag{50}$$

and

$$y_{11} = r_2s\theta_2 + r_7s\theta_7 - r_{10}s(\theta_{10} + \psi_1). \tag{51}$$

Four-Transducer Solution

The four-transducer solution was derived through equations already derived in the three-transducer solution section. Many viable combinations of these equations could perform the desired task, but these combinations relied on all four transducers yielding identical results. For the purpose of this derivation, equations 20, 21, 46, and 47 were used.

With θ_4 and θ_7 known from the derivations in the previous section, the vector loop equation that described this four-transducer solution was

$$^{A}\mathbf{R}_1 + {}^{A}\mathbf{R}_4 - {}^{A}_{B}T^{B}\mathbf{R}_9 + {}^{A}_{B}T^{B}\mathbf{R}_{10} - {}^{A}\mathbf{R}_7 - {}^{A}\mathbf{R}_2 = 0, \quad (52)$$

which by substituting equations 9 and 10, became

$$^{A}\mathbf{R}_4 - {}^{A}_{B}T^{B}\mathbf{R}_8 - {}^{A}\mathbf{R}_7 - {}^{A}\mathbf{R}_3 = 0. \quad (53)$$

The only unknown in this equation was ψ, but to avoid the ambiguities that arise from the use of the inverse sine or cosine, information from both scalar equations was taken into consideration. This was done by isolating the unknown quantity on the left side of the equation, dividing the y scalar component equation by the x scalar component equation, and solving for the unknown variable, resulting in

$$\psi = \tan^{-1}\left[\frac{r_4 s\theta_4 - r_7 s\theta_7 - r_3 s\theta_3}{r_4 c\theta_4 - r_7 c\theta_7 - r_3 c\theta_3}\right] - \theta_8. \quad (54)$$

Of course, to determine the correct heading of the machine, the quadrant information yielded by the x and y scalar equation components was utilized to eliminate ambiguities caused by the inverse tangent function. The mining machine's position was calculated in the standard manner, yielding

$$x_{11} = r_1 c\theta_1 + r_4 c\theta_4 - r_9 c(\theta_9 + \psi) \quad (55)$$

and

$$y_{11} = r_1 s\theta_1 + r_4 s\theta_4 - r_9 s(\theta_9 + \psi). \quad (56)$$

Testing and Backup Strategy

When measurements of any kind are performed, it is usually more important to know the reliability of the data than the actual data itself. If the data are not known to be reliable, the data are useless, since in mining operations, safety of personnel is of extreme importance. Thus, the redundancy provided by an additional sensor supplied a means of determining the accuracy of the data furnished. The four-transducer solution would always yield the correct position and heading, provided that the constraints of operation were met and the transducers were furnishing reliable data.

In order for the guidance system to operate properly, it was assumed that the attachment points of the transducers on the mining machine would always remain on the positive x side of the imaginary line connecting the transducer cable attachment points (fig. 9). If this constraint was not met, the heading and position data developed would be inaccurate. The best strategy, therefore, was to keep the transducer and cable attachment points separated by a suitable distance.

To determine if one of the transducers was furnishing unreliable data, a continuous check could be kept by cross comparing the four three-transducer solutions. If only one transducer was furnishing unreliable data, then the error could be determined to exist by the fact that all four solutions would disagree. If more than one transducer was furnishing inaccurate data, then it was possible that no error could be identified. While the possibility of more than one transducer failing at the same time in a manner yielding no identifiable error is small, it was theoretically possible in a roof fall or mechanical obstruction of multiple cables. The transducer data could be checked in such cases for unrealistically large rates of change in length, for underrange errors, and for overrange errors.

Since each three-transducer solution method yielded two possible positions and headings, in order for the three-transducer solutions to track the four-transducer solution, knowledge of the initial configuration of the mining machine and the subsequent changes in sign of the three-transducer solution equations was required. The initial configuration of the mining machine was assumed to be similar to that shown in figure 9 and was to be corroborated by the four-transducer solution. This configuration allowed the initialization of the signs in the heading equations

$$\psi_4 = a\epsilon - \theta_8 + \theta_4, \quad (57)$$

$$\psi_3 = \pi - a\nu - \theta_8 + \theta_5, \quad (58)$$

$$\psi_2 = b\eta - \theta_8 + \theta_6, \quad (59)$$

and

$$\psi_1 = \pi - b\zeta - \theta_8 + \theta_7, \quad (60)$$

where ψ_i = heading determined by a three-transducer solution, which excludes transducer i,

a = sign of ϵ and ν since both change signs at same time,

and b = sign of η and ζ since both change signs at same time,

to be such that both a and b were positive in the initial position and never change signs at the same time. Changing the signs of a and b could be performed by keeping track of both headings for each solution and choosing the appropriate sign and/or by noting the transition of the solution equations and using the sign of the angular velocity of the mining machine (ω). Determining the signs of a and b using the angular velocity of the mining machine was done in the following manner (fig. 9):

if $[(\nu\approx 0)$ and $(\omega<0)]$ or $[(\nu\approx\pi)$ and $(\omega>0)]$, then $a = -1$,

if $[(\nu\approx 0)$ and $(\omega>0)]$ or $[(\nu\approx\pi)$ and $(\omega<0)]$, then $a = 1$,

if $[(\eta\approx 0)$ and $(\omega<0)]$ or $[(\eta\approx\pi)$ and $(\omega>0)]$, then $b = -1$,

and if $[(\eta\approx 0)$ and $(\omega>0)]$ or $[(\eta\approx\pi)$ and $(\omega<0)]$, then $b = 1$.

Both of these methods relied on information external to the three-transducer solutions to determine the signs of a and b. If a transducer did fail, the error could be determined using equations 57 to 60 instead of equations 30, 37, 43, and 49.

ERROR ANALYSIS

Once the position and heading algorithm had been designed to reduce the possibility of mathematical errors induced by the configuration of the position and heading system, it was necessary to determine the source of other possible errors. These errors were introduced into the position and heading calculation through the inherent inaccuracies in the linear position transducers, the analog-to-digital (A/D) converter, and the sample rate.

The effects of these errors on the position and heading calculation depended to a large extent on the position and heading of the mining machine. While the determination of the maximum error required either an exhaustive trigonometric proof involving the taking of the partial derivatives of the governing equations or a numerical methods analysis, a preliminary numerical analysis utilizing a computer model of the position and heading system indicated that the overall position and heading system error was on the order of 0.25 ft and 3°, respectively. While error propagation could not be easily derived, the errors introduced, however, could be quantized.

LINEAR TRANSDUCERS

Linear transducers of the length necessary to perform the necessary tasks in the position and heading system (approximately 750 in) had a stated accuracy of 0.1 pct full scale, but typically had an accuracy of 0.05 pct full scale. Factory calibration information on five Rayelco[5] P-750A linear position transducers selected for use in the position and heading system can be found in appendix A. A preliminary analysis was performed on these calibration data to determine the calibration equations for each linear position transducer and for all five combined. The frequency distribution of error from the combined calibration equation was determined and appeared to be Gaussian in nature. (The calibration equations and error frequency distribution can be found in appendix B.) The only other accuracy concern for the linear position transducers was the effect of the dust and accumulations of dust on the transducer's wire itself. If this was discovered to be a problem, a submersible type of linear transducer could be used with water to flush the interior of the cable takeup housing.

ANALOG-TO-DIGITAL CONVERTER

The A/D conversion circuitry on the Intel remote control board (iRCB) 44/20A used to implement the position and heading system had an accuracy of about 0.035 pct full scale. These errors were due in part to nonlinearity, inherent quantizing errors, gain error, zero error, noise, and sample and hold dynamic error, and were found in the iRCB 44/20A's hardware user's manual. The specifications for the A/D converter can be found in appendix C.

SAMPLE RATE

Because of the processing capability available to the position and heading system through the Intel 8051 microprocessor running in a distributed control executive (iDCX 51) real-time multitasking environment, the number of position and heading calculations performed was on the order of 5 Hz. Considering, for example, that a Joy 16CM mining machine can attain speeds of up to 0.54 ft/s and angular velocities of up to 3.23°/s,[6] the sampling errors incurred of 0.1 ft and 0.6° could be considered acceptable in a mining environment. If greater accuracy is desired, a slower speed could be used or the machine could be stopped altogether.

CONCLUSIONS

A system to determine the position and heading of a mining machine during maneuvers required in the face area of an operating mine section was described. This system utilized four commercially available linear position transducers to obtain the required sensory data. The system employed sensor redundancy in its sensor fusion scenario to increase the system reliability. The derivation of the position and heading algorithm was presented and a preliminary error analysis was performed, which showed that the position and heading system had sufficient accuracy for mining application.

[5]Reference to specific products does not imply endorsement by the U.S. Bureau of Mines.

[6]Sammarco, J. J. Closed Loop Control for a Continuous Mining Machine. BuMines RI 9209, 1988, 17 pp.

APPENDIX A.–LINEAR POSITION TRANSDUCER CALIBRATION DATA

(Range, 750 in; cable tension, 24 oz; potential resistance, 500 ohms; excitation, 10 V dc)

Calibration step	Travel, in	Output, V	Ideal, V	Delta, mV
		TRANSDUCER 1[1]		
1	0.00	0.035	0.035	0
2	187.50	2.463	2.463	0
3	357.00	4.889	4.891	2
4	562.50	7.314	7.319	5
5	750.00	9.747	9.747	0
		TRANSDUCER 2[2]		
1	0.00	0.028	0.028	0
2	187.50	2.462	2.460	2
3	357.00	4.891	4.893	2
4	562.50	7.321	7.325	4
5	750.00	9.758	9.758	0
		TRANSDUCER 3[3]		
1	0.00	0.034	0.034	0
2	187.50	2.454	2.461	7
3	357.00	4.887	4.888	1
4	562.50	7.314	7.316	2
5	750.00	9.743	9.743	0
		TRANSDUCER 4[4]		
1	0.00	0.030	0.030	0
2	187.50	2.461	2.465	4
3	357.00	4.898	4.901	3
4	562.50	7.339	7.336	3
5	750.00	9.771	9.771	0
		TRANSDUCER 5[3]		
1	0.00	0.026	0.026	0
2	187.50	2.448	2.452	4
3	357.00	4.877	4.878	1
4	562.50	7.298	7.305	7
5	750.00	9.731	9.731	0

[1]0.05 pct full scale, 1.29 mV/(V/in) position.
[2]0.05 pct full scale, 1.30 mV/(V/in) position.
[3]0.07 pct full scale, 1.29 mV/(V/in) position.
[4]0.04 pct full scale, 1.30 mV/(V/in) position.

APPENDIX B.–CALIBRATION EQUATIONS AND ERROR FREQUENCY DISTRIBUTION

Output (Qo), in volts, for the five linear position transducers, as described in appendix A, was used to calculate the slopes, intercepts, and standard deviations of the calibration equations for each of the five linear position transducers and for all five combined. The general calibration equation was determined to be

$$Qi = \frac{Qo - 0.02944}{0.012959} \pm 2.050786 \text{ in},$$

with maximum error = 1.694514 in.

The calibration equation for transducer 1 was determined to be

$$Qi = \frac{Qo - 0.03460}{0.012947} \pm 0.89625 \text{ in},$$

with maximum error = 0.239444 in.

The calibration equation for transducer 2 was determined to be

$$Qi = \frac{Qo - 0.02820}{0.012970} \pm 1.014279 \text{ in},$$

with maximum error = 0.223591 in.

The calibration equation for transducer 3 was determined to be

$$Qi = \frac{Qo - 0.03080}{0.012948} \pm 1.120895 \text{ in},$$

with maximum error = 0.35526 in.

The calibration equation for transducer 4 was determined to be

$$Qi = \frac{Qo - 0.02780}{0.012992} \pm 3.201727 \text{ in},$$

with maximum error = 0.246305 in.

The calibration equation for transducer 5 was determined to be

$$Qi = \frac{Qo - 0.02580}{0.012940} \pm 2.772926 \text{ in},$$

with maximum error = 0.030911 in.

The error frequency distribution for the general calibration equation is as shown in figure B-1.

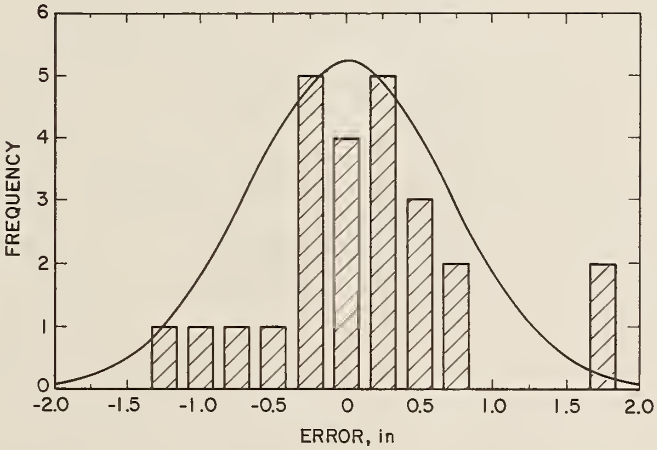


Figure B-1.–General calibration equation error frequency distribution.

APPENDIX C.–CONVERSION SPECIFICATIONS FOR INTEL REMOTE CONTROL BOARD 44/20A ANALOG-TO-DIGITAL CONVERTER

Linearity	To within ±0.75 LSB.
Differential linearity	To within ±0.75 LSB.
Inherent quantizing error	±0.5 LSB.
System accuracy:	
Gain = 1	To within ±0.035 pct FSR.
Gain = 10	To within ±0.05 pct FSR.
Gain = 100	To within ±0.07 pct FSR.
Gain = 500	To within ±0.15 pct FSR.
Gain error	Adjustable to zero.
Zero error	Do.
Channel crosstalk	-80 dB at 1 kHz.
Noise (A/D converter)	0.2 LSB RMS.
Instrumentation amplifier settling time:	
Gain = 1	20 μs.
Gain = 10	20 μs.
Gain = 100	100 μs.
Gain = 500	100 μs.
A/D conversion time: All gains	30 μs.
Maximum A/D throughput:	
Gain = 1	20,000 samples per second.
Gain = 10	Do.
Gain = 100	7,500 samples per second.
Gain = 500	Do.
Sample and hold feedthrough attenuation	-80 dB at 1 kHz.
Sample and hold dynamic error	±0.75 LSB.
Offset drift (gain = 1)	100 μV/°C.
Input offset drift multiplied by gain	3 μV/°C.
Gain drift:	
Gain = 1	32 ppm of FSR per degree Celsius.
Gain = 10	40 ppm of FSR per degree Celsius.
Gain = 100	65 ppm of FSR per degree Celsius.
Gain = 500	75 ppm of FSR per degree Celsius.
Monotonocity	Monolithic, 0° to +60° C.
Common mode rejection ratio:	
Gain = 1	70 dB at 60 Hz, 1 kohm unbalance.
Gain = 500	100 dB at 60 Hz, 1 kohm unbalance.
Amplifier input noise	2 μV RMS.
Channel-to-channel input voltage error	±40 μV.
Resolution	12 bits.

FSR Full-scale reading.
LSB Least significant bits.
RMS Root mean square.

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